NEMO-surge: Setting up an accurate tidal model

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Technical Report No: 610
11th May 2016

Contents

NEMO-surge sensitivity testing....1

Summary....2

1. Introduction....3

2. The NEMO-surge configuration....4

3. Method....4

3.1 Control Experiment....4

3.2 Comparative Data....5

3.3 Experiment design....5

4. Amended Bathymetry experiments....6

4.1 Revised bathymetries....6

4.2 Results....9

5. Amended bottom friction coefficient....14

5.1 Bottom friction formulation....14

5.2 Results....14

6. Tidal boundary forcing....17

6.1 Harmonic constituents....17

6.2 Results....17

7. NEMO-surge versus CS3X comparison....19

8. Discussion and conclusions....24

References....25

Summary

A prototype NEMO-surge model has been developed as part of a joint project between the Met Office and the National Oceanographic Centre (NOC). The model has been set up and extensively tested in tide-only mode. When setting up a model to predict storm surges it is vital to get the underlying tidal solution as accurate as possible. The sensitivity of the model tide to changes in the bathymetry, bottom friction and the tidal boundary forcing has been assessed and is presented here. The tide produced by NEMO-surge is also compared to the tide produced by the existing operational surge model (CS3X), the harmonically predicted tide and tidal harmonics based on long-period observations at tide gauges. Following these tests a tidal configuration of NEMO-surge has been finalised which provides the basis for meteorologically driven runs.
There are three main parameters which contribute to producing an accurate model tidal solution. They are (in order of application): boundary tidal input, bathymetry and bottom friction coefficient parameter.

Sensitivity tests have shown that the model tide is most sensitive to changes in the bathymetry, highlighting the need for careful choice of the bathymetry used, with effort to ensure this best represents reality. It is also sensitive to changes to the bottom friction coefficient, meaning this can be used to fine tune the model. However the model shows little sensitivity to additional tidal constituents being used in the boundary forcing, over and above the 14 constituents common to CS3X and the Met Office's baroclinic NEMO shelf seas model (implying the majority of the signal is well captured by the 14 constituents). Applying a set of 26 constituents, tested in this study and used in the operational CS3X model, is still advisable for the small impacts this has, however any further constituents are felt unnecessary.

The finalised tidal configuration shows at least comparable performance to CS3X. The majority of model versus observation statistics from UK ports with Class A tide gauges show improvements, although some locations show small degradations in performance. Overall it has been demonstrated that the NEMO-surge model is well placed to replace CS3X in terms of tidal performance.

1. Introduction

As part of efforts to modernise and homogenise ocean modelling systems run operationally at the Met Office, a project has been undertaken by NOC and the Met Office to assess whether a two-dimensional (2-d) barotropic configuration of the Nucleus for European Modelling of the Ocean (NEMO; Madec, 2014) can be viably run as a surge model. If successful, this project will lead to the NEMO-surge configuration becoming the UK operational system and replacing the CS3X surge model, described in Flather (1994), which also runs as an ensemble system (Flowerdew et al. 2010) to provide the background guidance for the UK's storm surge warning service.

To provide high quality forecasts for UK waters, a candidate surge model must be able to demonstrate good performance in prediction of the tide, in order to account for the strong two-way interactions between tide and surge in this region; see Rossiter (1961) and Horsburgh and Wilson (2007). The effect of wind stress is inversely dependent on water depth, leading to a major sensitivity when the tide range is significant compared to the mean water depth. In addition storm surges act to advance the tide (or retard the tide in the case of negative surges) due to increased water depth increasing the speed of the shallow water wave.

A number of experiments have been undertaken with the prototype NEMO-surge configuration in order to assess its performance as a tidal model. These included sensitivity studies, which assessed the impact of bathymetry, bottom friction, and the number of tidal harmonics applied at the boundaries. In each case results compared model output with observations from the UK's National tide gauge network. Following selection of the most suitable bathymetry and tuning of the bottom friction, a best performing tidal configuration was finalised and compared with the present operational surge model, CS3X, which provides a target performance level.

Details of the NEMO-surge configuration are provided in section 2. The control member and the experiment format and assessment are described in section 3. A discussion of bathymetry modifications and results from these runs are given in section 4. The impacts of amending the bottom friction are shown in section 5. Section 6 focuses on the impact of the number of tidal constituents being applied at the boundaries. A best performing NEMO-surge tide-only configuration is compared to the CS3X model in tide-only mode in section 7. Finally, comparison of these sensitivities relative to each other and conclusions are given in section 8.

2. The NEMO-surge configuration

NEMO-surge is a two dimensional, barotropic configuration of the NEMO model. The configuration assessed in this report has a horizontal resolution of approximately 7km, with a domain spanning from 20^{o} East to 13^{o} West and from 40^{o} to 60^{O} North (the full domain is shown in Figure 5). The configuration is designed to be analogous to the three-dimensional baroclinic AMM7 configuration, as described in O'Dea et al (2012).

The storm surge code is based on version 3.6 of NEMO (Madec, 2014), with local modifications that enable the model to run using a single vertical level assuming barotropic flow. Code modifications to enable running the model in this mode involve removing calls to vertical processes, such as vertical diffusion and vertical advection (using a pre-compile key), as well as the introduction of a simple horizontal pressure gradient scheme designed for use with a single terrain following coordinate. In order to further improve run efficiency unnecessary processes, related to modelling of tracers and vertical exchanges, are removed.

3. Method

3.1 Control Experiment

Throughout these sensitivity studies a consistent control experiment was defined. The control is based on the AMM7 configuration, which uses a bathymetry based on a product provided by the North Sea Operational Oceanography (NOOS) consortium (NOOS system, 2015). For surge forecasting purposes, a small number of manual edits were applied to better define the coastline and ensure that, where appropriate, features such as islands and small channels were represented[1]. A minimum depth of 6m has been applied across the domain; with the exception of the Bristol Channel and Gulf of St Malo, where a 10m minimum depth is used due to the exceptional tidal range in these regions. Bottom friction is applied using a non-linear parameterisation with a constant coefficient of 0.0025 (see section 5.1). Tidal forcing from 26 tidal constituents is applied on the domain boundaries using a Flather formulation. A larger domain tide-surge model covering the North-East Atlantic (Flather, 1981) was run in tide-only mode for a 12-month period. A harmonic analysis produced 26 constituents which were then interpolated to the AMM7 grid. Boundary values were then extracted

[1] Key changes were applied around the Thames estuary, Solent, Humber and Morecambe Bay in order to achieve a sensible geographic match between model extent and location of UK tide gauges.

for use in NEMO-surge. Tidal forces within the domain are accounted for with a 'body force' parameterisation.

3.2 Comparative Data

Figure 1 Location of Class A tide gauges

The UK National Tide Gauge Network of sea level gauges is run by the Tide Gauge Inspectorate at NOC on behalf of the Environment Agency (EA), recording tidal elevations at 44 locations around the UK coast. Data from the UK National Tide Gauge Network are quality controlled and archived by the British Oceanographic Data Centre. Logging and telemetry systems transfer data to the Met Office and then to the EA in near real-time. Harmonic analysis of these data over a period of 19-years gives a set of harmonic constants for each port from which tidal predictions can be calculated and against which our models are validated. Figure 1 shows the locations of all gauges in the UK tide gauge network. More information can be found in UK National Tidal and Sea Level Facility (2013).

3.3 Experiment design

For each experiment the model was run for 2 years, 2003 and 2004, in tide only mode. The Sea Surface Height (SSH) was output hourly over the entire domain. The year 2003 was used to spin-up the model; results from 2004 were then harmonically analysed for 50 tidal constituents to give a modelled phase and amplitude for each constituent (note this is significantly more constituents than are input at the model boundary, but are used to account for harmonics generated internally in the model as a result of wave propagation in shallow water and around complex coastlines).

For 14 main tidal constituents the values of phase and amplitude derived from the model were compared with values derived from the observed data. The following parameters were calculated for each tide gauge location:

1. H_m-H_o: The difference between the modelled and observed amplitude (in m).

2. G_m-G_o: The difference between the modelled and observed phase (in degrees, where a positive value implies that high water in the model occurs later than in the observations).
3. *DHPm*: The difference in amplitude given as a percentage error of the modelled value.
4. *Hs*: The error in the complex plane, defined as $Hs = (h_1^2 + h_2^2)^{½}$, where $h_1 = H_m cos(G_m) - H_o cos(G_o)$ and $h_2 = H_m sin(G_m) - H_o sin(G_o)$

The individual tide gauge errors were combined to obtain overall statistics for bias and root mean squared (RMS) error in amplitude, phase and complex error. More information on the observation data and method of comparison can be found in Furner et al. (2015).

4. Amended Bathymetry experiments

Tides and surges travel through the ocean as shallow water waves, as they have long wave lengths compared to water depth. The wave speed can therefore be approximated as

$$c = \sqrt{gh},$$

where g is acceleration due to gravity and h is water depth.

As such the speed of wave propagation is directly dependant on water depth (so that wave speeds are faster in deeper water). Therefore differences in the bathymetry used in the model have an impact on wave speed and thus the timing of the tide. In addition, shoaling characteristics of the tidal wave are affected by gradients in wave speed. Tests were undertaken to investigate these effects, looking at the spatial extent of the impacts, and the magnitude of the differences. A number of tests were run with various alterations to the bathymetry, as well as a test with a completely new bathymetric product, the EMODnet bathymetry (emodnet.eu 2015).

4.1 Revised bathymetries

The NOOS bathymetry and the bathymetry used in the current operational storm surge model, CS3X, were visually compared. This highlighted a number of notable differences between the two bathymetries. Those believed to be likely to impact results were differences in the depths of the North Sea, the inclusion (or not) of the Waddenzee and differences in the width of the Fair Isle gap.

The North Sea, particularly near the East coast of the UK, is notably shallower in the NEMO-surge control than in the CS3X bathymetry (see figure 1). This should lead to slower speeds of tidal propagation in NEMO-surge, affecting tidal phase in that area of the model and, possibly, elsewhere in the domain. To test this effect runs were undertaken using an amended bathymetry, which was based on the NOOS bathymetry but altered so that depths less than 100m in the southwest part of the North Sea were replaced with values close to those in the CS3X. This will be referred to as the North Sea experiment, or the NS experiment.

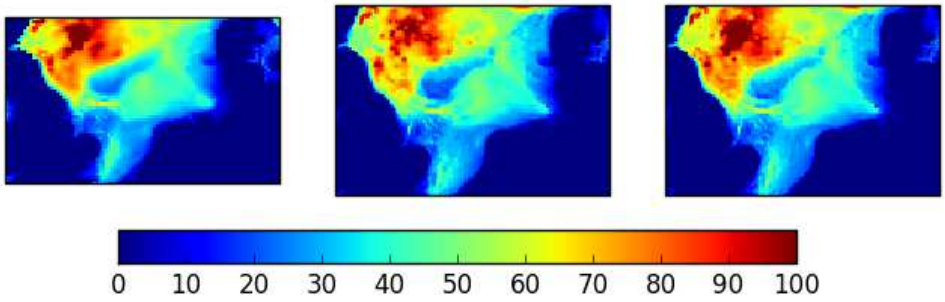

Figure 2: North Sea bathymetry from CS3X model (left), NEMO control (middle) and NS (right)

The CS3X bathymetry has an open Waddenzee, as shown in figure 3, whereas in the control run this area is treated as land. To assess whether this variation in domain size affects North Sea tides the Waddenzee area was manually edited to closer match that used in CS3X (whilst the rest of the domain was left to match the control run bathymetry). This run is referred to as the WZ experiment.

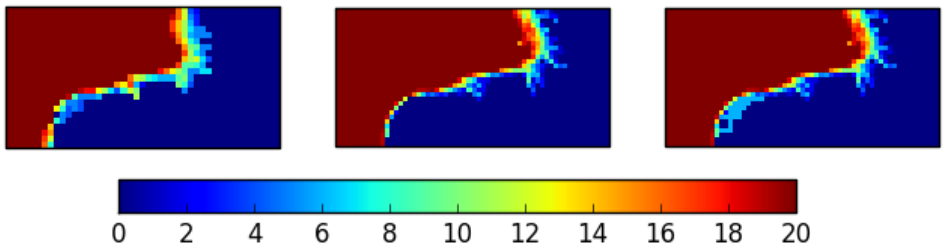

Figure 3: Bathymetry in the Waddenzee area from CS3X model (left), NEMO control (middle) and WZ (right)

The width of the Fair Isle gap differs between the NOOS bathymetry and that used in CS3X. To test how this might affect propagation of the tidal wave into the North Sea, a new bathymetry was created by modifying the NOOS bathymetry in the region of the Fair Isle gap to increase the width, making it more similar to the CS3X bathymetry in this region. This modification involved far fewer grid point edits than the NS and WZ experiments (figure 4). This is hereafter referred to as the FIG experiment.

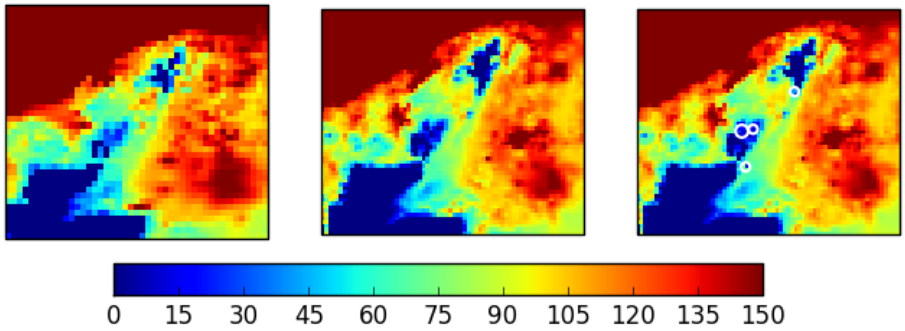

Figure 4: Bathymetry near the Fair Isle gap from CS3X model (left), NEMO control (middle) and FIG (right) with white circles indicating where changes have been made

Finally a test was run with an alternative bathymetry derived from the EMODnet dataset. Compared to the other bathymetries used in this study this has a more modern and better understood provenance, having been derived from products generated in a recent project to homogenise survey data in European waters. The underlying high resolution bathymetry is provided as a lowest astronomical tide product so, in addition to interpolation onto the 7km grid, the bathymetry is converted to the mean sea-level datum used by the model based on tidal ranges extracted from the CS3X model. For this experiment minimum depths were again set at 6m, except in the Bristol Channel and Gulf of St Malo, where the value was 10m. The land sea mask is based on the EMODnet data. The EMODnet bathymetry is shown in figure 5, which indicates that in a number of shelf seas regions (e.g. Western Isles of Scotland, southeast Scotland to northeast England, Norfolk to the Thames estuary) this is up to 20% deeper than the control experiment (NOOS) bathymetry.

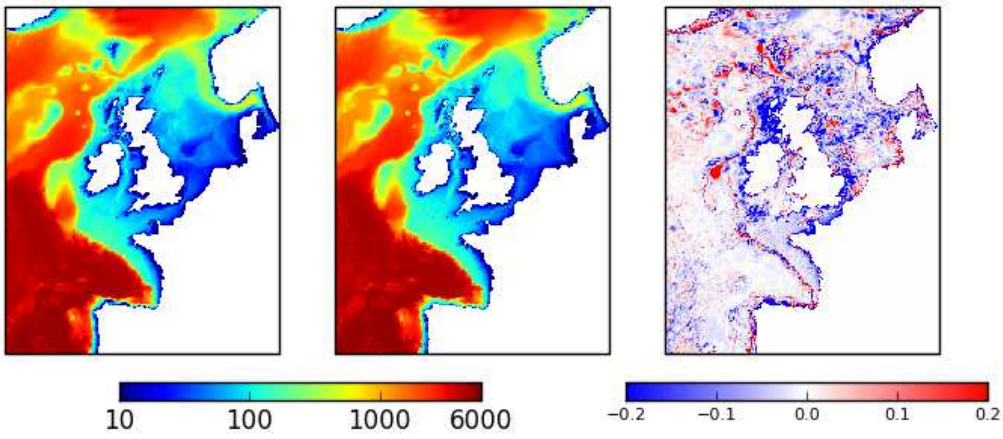

Figure 5: NEMO control bathymetry (left), EMODnet bathymetry (middle) and normalised difference (control minus EMODnet/control) (right)

4.2 Results

Figures 6-9 show the differences in the phase and amplitude of the M2 constituent between the control run and the 4 bathymetry experiments. The M2 constituent is one of the most dominant in this region, so much of this report focuses on changes to the M2 constituent as a key indicator of model behaviour.

The tide travels into the domain from the Atlantic Ocean where, in the northwest European shelf seas, it travels as a Kelvin wave circulating clockwise around land (i.e. keeping the land to the right). Within this domain tides travel through the Fair Isle gap into the North Sea and down the East coast of the UK, as well as travelling east along the coastlines of Belgium, the Netherlands and Germany. The tide then travels north and east up and along the coastlines of Denmark and Norway.

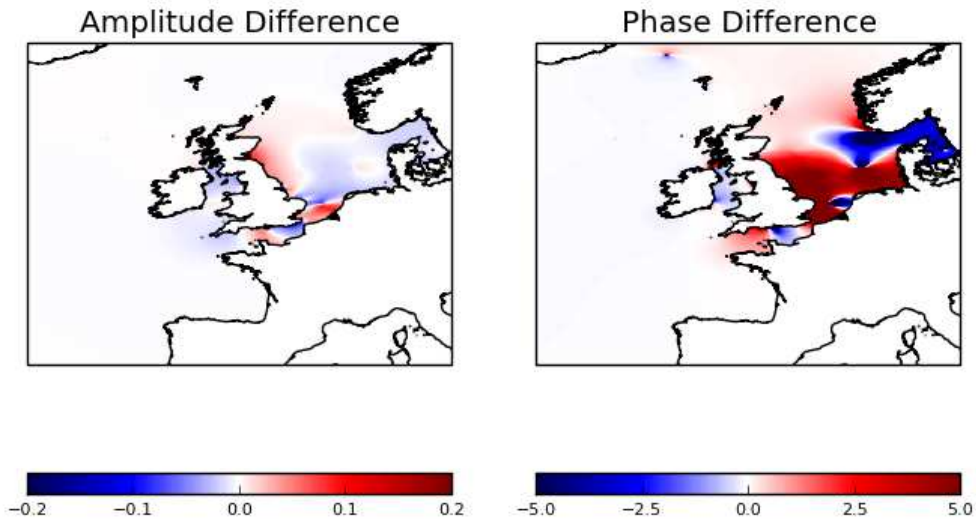

Figure 6: Differences (control-exp) in amplitude (m) and phase (degrees) for M2 constituent between control and NS experiment

The NS experiment, which contains the largest amendments to the NOOS bathymetry (i.e. excluding the EMODnet experiment for the time being), understandably has large differences in the phase over much of the North Sea. Large areas show differences of up to 10 degrees, which equates to the M2 wave reaching that point around 20 minutes later/earlier. For much of the central and southern North Sea the phase is notably smaller in the NS experiment than in the control, showing the tide is travelling faster in the area where the bathymetry was adjusted. Some locations remote from the adjusted part of the domain are also affected, in particular the Skagerrak and Kattegat where the phase is larger for the NS experiment. Interestingly there are also impacts to the phase in the English Channel and as far as the northern Irish Sea, implying the differences are large enough to propagate with the tide. The impact on amplitudes is small compared to

that of the phase, with amplitude differences for the M2 constituent reaching a maximum of ~12cm, and showing differences of up to 5cm for much of domain. This is small compared to the M2 amplitude, which measures over 4m in some parts of the domain. The amplitude differences show a similar spatial impact to the phase, with some changes as far as the Irish Sea.

The WZ experiment impacts the phase of the tide for coastlines along which the tidal wave travels (anti-clockwise around the North Sea) after the WaddenZee area. The changes give rise to an increase in phase of approximately 5 degrees (which corresponds to a later arrival of high water by around 10 minutes) over a fairly large area of the eastern North Sea. Whilst the spatial extent of these impacts is initially surprising given the limited nature of the change, it is perhaps less so when considering the proximity of the change to the amphidromes in the southern part of the North Sea. It should be noted that comparisons to observations discussed later will only consider observations from the UK tide gauge network and, as a result, do not pick up the majority of signal from this change. This highlights the need for better spatial coverage when using observational comparisons to evaluate the overall model performance. Including the WZ area has a very limited impact on tidal amplitudes over the entire domain, with differences in most locations being less than 5cm for the M2 constituent.

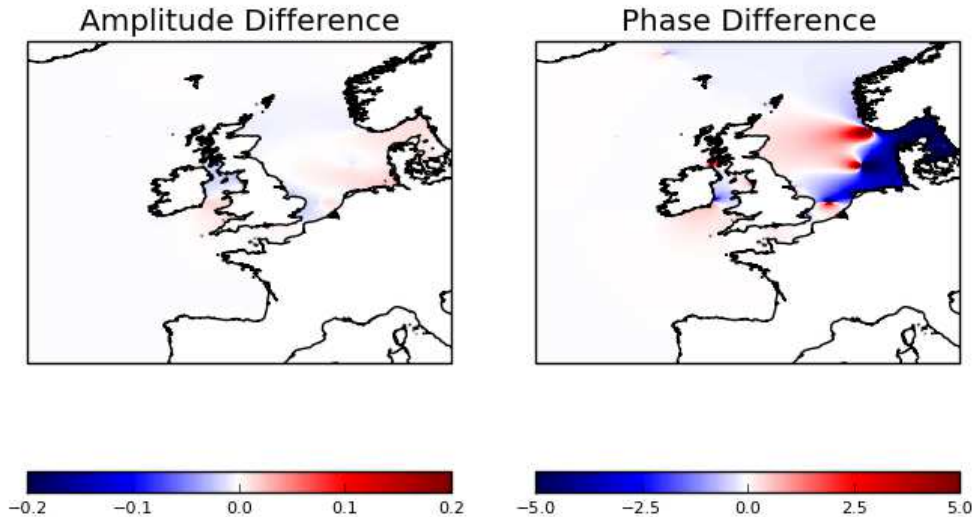

Figure 7: Differences (control-exp) in amplitude (m) and phase (degrees) for M2 constituent between control and WZ experiment

The FIG experiment again shows effects that are not localised to the area where the bathymetry has been amended but propagate with the tide through the domain. The change has impacts throughout the North Sea, with a general decrease in phase indicating an earlier arrival of high/low water than in the control experiment. The magnitude of the changes are considerably smaller than in the NS and WZ experiment with phase changes of around 2 or 3 degrees; however only a handful of grid points were changed here, so small effects are not unexpected. Amplitude changes are also small, at less than 2cm for the majority of the domain.

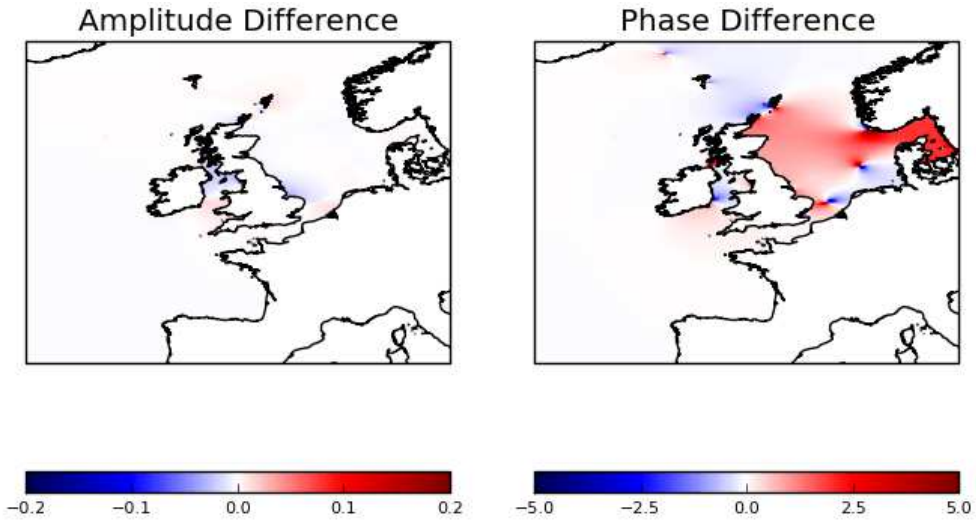

Figure 8: Differences (control-exp) in amplitude (m) and phase (degrees) for M2 constituent between control and FIG experiment

The EMODnet experiment shows wide scale impacts on tidal phase (figure 9), with a large decrease in phase (~20 degrees) indicating earlier tide arrival over much of the domain compared to the control. The impact on amplitude is more varied, with some areas showing increases and other areas showing decreases; the maximum changes are close to double those found in the NS experiment. As would be expected given the large scale change to the bathymetry, the impacts of using the EMODnet bathymetry are far greater in magnitude than any of the other bathymetric experiments, as well as being of a far greater spatial extent.

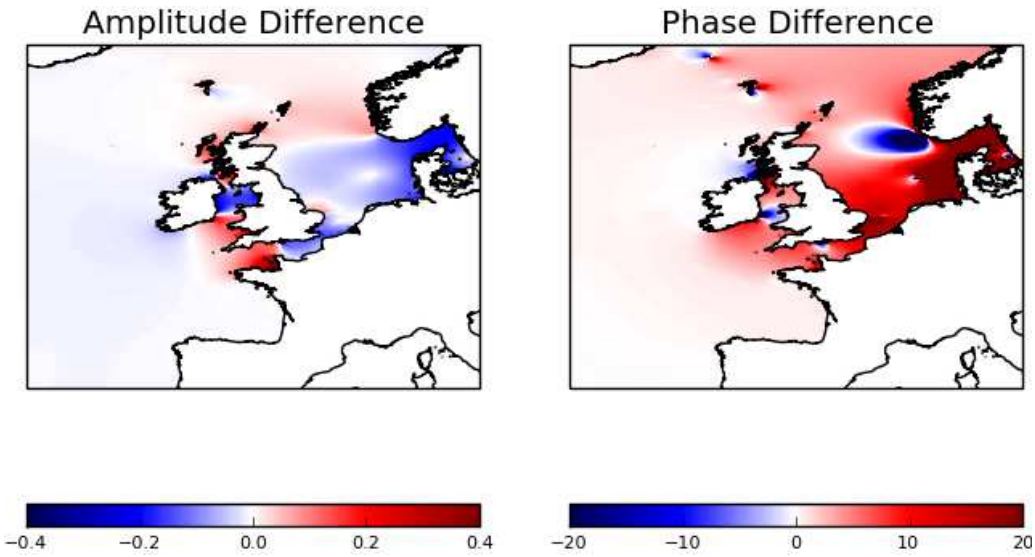

Figure 9: Differences (control-exp) in amplitude (m) and phase (degrees) for M2 constituent between control and EMODnet experiment

Results for comparisons of the four runs against the combined UK tide gauges are shown in table 1. It should be noted that this assesses only the impact on the UK coastline, and therefore will imply greater sensitivity to some changes purely because of the spatial bias in this comparison. These data show the sensitivity of the tide on the UK coastline to these changes, and not the sensitivity of the model more generally. The lowest errors for each metric and tidal constituent are shown in green. It can be seen that using the EMODnet bathymetry gives the best results overall, particularly in terms of systematic biases and complex errors. The NS experiment also gives the lowest RMS amplitude errors and lowest RMS phase errors for a large number of tidal constituents, and is generally an overall improvement on the control. The results imply that the bathymetry used in the control experiment does not perform well for tidal runs, and that some large scale changes are required. As the EMODnet bathymetry gives the lowest overall errors when assessing against the UK tide gauges, and is also a chart derived product with known provenance, it is recommended that this is used as the baseline bathymetry for all future runs with NEMO-surge.

Table 1: Summary results from bathymetry sensitivity testing – overall errors in model-observation amplitude (m), phase (degrees) and complex error from combined UK tide gauge locations

Tidal constituent	Mean amplitude error					RMS amplitude error				
	Control	NS	WZ	FIG	EMODnet	Control	NS	WZ	FIG	EMODnet
Q1	-0.5	-0.49	-0.5	-0.5	-0.51	0.65	0.64	0.65	0.66	0.68
O1	-0.61	-0.61	-0.61	-0.63	-0.31	1.17	1.04	1.17	1.18	0.66
P1	0.09	0.13	0.1	0.09	0.52	0.49	0.45	0.49	0.49	0.78
K1	-1.16	-1.12	-1.16	-1.17	-0.41	1.49	1.43	1.49	1.49	1.07
2N2	1.25	1.27	1.24	1.25	1.14	2.02	2.02	2.01	2.01	2.03
MU2	-0.09	-0.07	-0.1	-0.11	-0.06	1.51	1.41	1.52	1.5	1.61
N2	-1.94	-1.87	-1.94	-1.94	-1.58	3.32	3.16	3.36	3.34	3.09
NU2	0.46	0.47	0.46	0.46	0.18	0.8	0.84	0.8	0.81	0.58
M2	-7.98	-7.7	-7.98	-8.01	-10.5	14.26	14.09	14.57	14.5	14.49
S2	-1.77	-1.64	-1.7	-1.72	-1.2	4.62	4.41	4.66	4.64	3.31
K2	-0.68	-0.63	-0.66	-0.66	-0.43	1.64	1.56	1.66	1.65	1.35
M4	0.09	0.29	0.8	0.76	1.52	6.77	6.45	6.88	6.81	6.64
MS4	0.38	0.48	0.77	0.77	1.3	5.13	4.81	5.22	5.16	4.4
M6	0.23	0.18	0.03	0.18	0.18	2.17	2.4	2.16	2.21	1.72
Tidal constituent	**Mean phase error**					**RMS phase error**				
	Control	NS	WZ	FIG	EMODnet	Control	NS	WZ	FIG	EMODnet
Q1	8.26	7.4	8.23	8.22	1.06	18.73	18.49	18.75	18.76	18.59
O1	10.29	8.21	10.26	10.22	1.77	13.52	12.36	13.49	13.53	7.87
P1	-0.21	-2.15	-0.18	-0.31	-6.64	14.98	13.45	15.07	15.02	11.65
K1	-1.05	-3.1	-1.06	-1.09	-7.36	12.51	11.11	12.6	12.57	10.35
2N2	-15.65	-17.43	-15.79	-16.04	-13.01	36.23	38.67	36.39	36.54	40.44
MU2	10.3	7.63	10.26	9.92	-9.87	21.48	20.45	21.61	21.82	32.66
N2	6.51	4.2	6.3	6.09	2.64	11.01	8.47	11.43	11.13	14.82
NU2	-2.83	-4.77	-3.01	-3.22	-4.37	12.88	11.7	12.91	12.76	28.67
M2	3.47	1.32	3.33	3.1	-0.71	10.58	8.25	10.8	10.5	10.31
S2	5.88	3.58	5.83	5.57	-1.4	9.44	6.11	9.68	9.3	7.69
K2	5.43	3.11	5.37	5.11	-2.05	9.15	5.98	9.38	8.99	9.08
M4	31.6	20.34	33.35	31.2	3.08	52.81	54.52	56.84	53.57	30.4
MS4	27.96	19.51	32.5	30.46	2.68	50.99	56.12	53.9	51.24	35.33
M6	27.5	20.36	22.59	24.35	-4.88	58.96	54.83	63.89	57.31	71.55
Tidal constituent	**Mean complex Error**					**RMS complex error**				
	Control	NS	WZ	FIG	EMODnet	Control	NS	WZ	FIG	EMODnet
Q1	0.75	0.73	0.75	0.75	0.77	0.79	0.77	0.79	0.8	0.85
O1	1.75	1.36	1.75	1.75	0.7	1.92	1.48	1.93	1.92	0.81
P1	0.76	0.68	0.77	0.77	0.92	0.86	0.76	0.87	0.86	0.98
K1	1.99	1.83	2	2	1.56	2.28	2.11	2.29	2.29	1.95
2N2	2.62	2.69	2.63	2.65	2.92	3.96	4.03	3.97	3.97	4.14
MU2	2.19	2.03	2.15	2.14	2.01	2.87	2.65	2.85	2.82	2.53
N2	5.87	4.89	5.87	5.77	3.47	6.84	5.57	6.83	6.72	4.02
NU2	1.09	1.06	1.09	1.09	1.23	1.29	1.21	1.29	1.28	1.34
M2	23.77	19.23	23.7	23.17	16.16	29.23	22.19	29.26	28.62	18.99
S2	8.95	7.42	8.93	8.75	5.07	10.96	9.01	10.91	10.72	5.86
K2	2.61	2.13	2.61	2.55	1.92	3.13	2.54	3.14	3.08	2.17
M4	7.72	7.59	8.08	7.93	5.6	9.65	9.65	10.07	9.89	7.95
MS4	5.59	5.38	5.81	5.73	3.77	7.52	7.38	7.76	7.65	5.75
M6	2.5	2.26	2.4	2.43	1.87	3.34	3.12	3.23	3.27	2.31

5. Amended bottom friction coefficient experiments

5.1 Bottom friction formulation

Within NEMO various bottom friction parameterisations are available. Due to the overall simplicity of this model it was felt the non-linear parameterisation as described in Madec (2014) was most appropriate. This scheme assumes the flux due to bottom friction is proportional to the velocity of the bottom layer (the barotropic velocity in our 1 layer model) using the equation

$$f = \frac{r}{h}\boldsymbol{U} ,$$

where r is a drag coefficient and h is the height of the bottom box (the height of the entire water column in this 1 layer set up). We use a non linear formulation for bed stress such that r is correlated to current speed by the equation

$$r = A\sqrt{u^2 + v^2},$$

where A is a user-defined coefficient.

The sensitivity of the model to the value of A was assessed by running the model with the control value of 0.0025 (used in CS3X), and values of 0.002 and 0.003. Assessment of tidal propagation was carried out as described in section 3.

5.2 Results

Figures 10 and 11 show the differences in the phase and amplitude of the M2 constituent between the control run and the two bottom friction experiments.

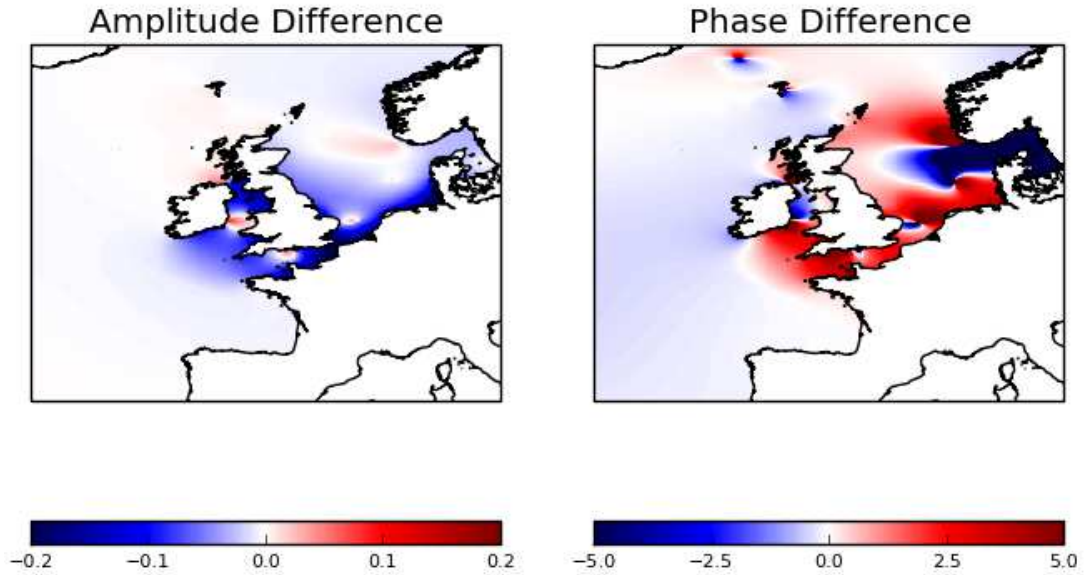

Figure 10 Differences (control-exp) in amplitude (m) and phase (degrees) for M2 constituent between control and A=0.002 experiment

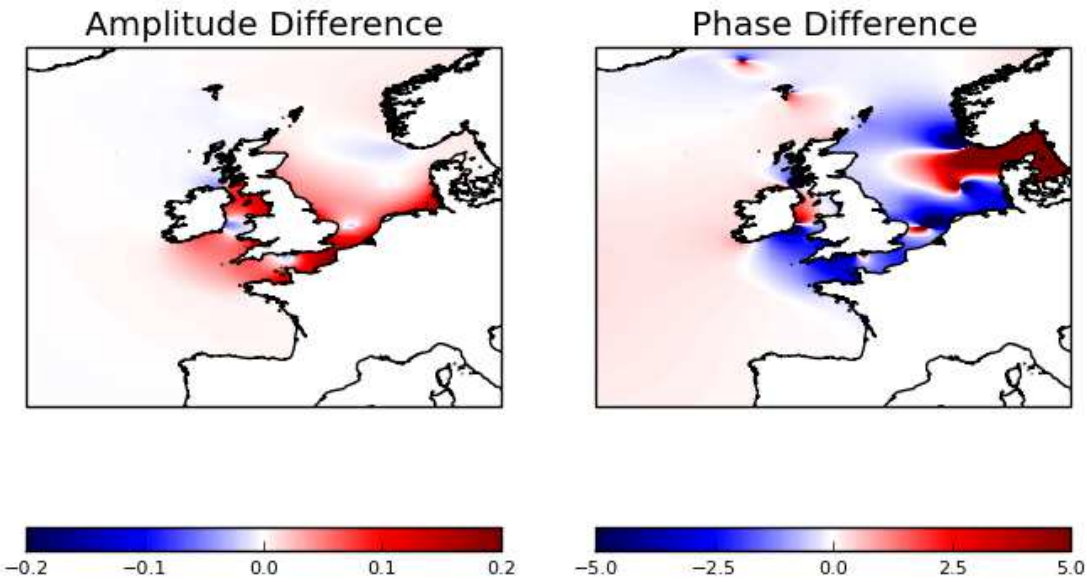

Figure 11: Differences (control-exp) in amplitude (m) and phase (degrees) for M2 constituent between control and A=0.003 experiment

The two experiments show opposite effects. Decreasing the bottom friction leads to a increase in amplitudes in most areas and an decrease in phase over much of the domain, especially on the continental shelf. Increasing the bottom friction decreases amplitude and increases phase. Whilst the impacts on the phase are comparable to those shown through the bathymetry experiments, the impacts on amplitude are more spatially consistent than those achieved by changing the bathymetry and are greater in magnitude than the differences obtained with the NS, WZ and FIG experiments.

Summary statistics for the three runs are shown in table 2. As was noted before, the table shows only the impacts on the UK coastline. However, as these runs produce differences which are more spatially homogenous, the results shown give a useful indication of overall model sensitivity. For the control run using the NOOS bathymetry (which was biased high in terms of mean phase) lower values of the coefficient A improve mean phase errors. RMS amplitude errors show more variation, with some tidal constituents showing improvements with lower values, whilst others are improved with higher values of A. These relative changes would have a different impact dependent on the background errors associated with the baseline bathymetry, i.e. a domain-wide change in bottom friction provides a coarse mechanism for tuning the model results, with the best choice of A dependent on the bathymetry.

Thorough tuning of the coefficient A was carried out on a finalised bathymetry, based on the EMODnet data. In these experiments the value 0.0024 was found to give the best overall match to observational data. Results from this run are given in section 7.

Table 2: Summary results from sensitivity testing of bottom friction coefficient – overall errors in amplitude (m), phase (degrees) and complex error from combined UK tide gauge locations

	Mean amplitude error			RMS amplitude error		
Tidal Constituent	A=0.002	Control	A=0.003	A=0.002	Control	A=0.003
Q1	-0.4	-0.5	-0.57	0.53	0.65	0.76
O1	-0.27	-0.61	-0.87	0.94	1.17	1.44
P1	0.2	0.09	0.02	0.6	0.49	0.43
K1	-0.88	-1.16	-1.39	1.33	1.49	1.67
2N2	1.37	1.25	1.12	2.21	2.02	1.83
MU2	0.1	-0.09	-0.26	1.42	1.51	1.8
N2	-0.18	-1.94	-3.43	2.35	3.32	4.9
NU2	0.75	0.46	0.2	0.99	0.8	0.78
M2	1.2	-7.98	-15.67	11.74	14.26	22.17
S2	2.64	-1.77	-5.23	6.15	4.62	7.62
K2	0.58	-0.68	-1.66	1.63	1.64	2.58
M4	1.71	0.09	-1.13	7.03	6.77	6.83
MS4	1.59	0.38	-0.53	5.73	5.13	4.85
M6	0.19	0.23	0.32	2.21	2.17	1.95
	Mean phase error			**RMS phase error**		
Tidal Constituent	A=0.002	Control	A=0.003	A=0.002	Control	A=0.003
Q1	5.66	8.26	10.45	17.25	18.73	20.37
O1	7.38	10.29	12.57	10.07	13.52	16.14
P1	-1.46	-0.21	1.1	14.73	14.98	15.62
K1	-2.45	-1.05	0.3	12.01	12.51	13.22
2N2	-17.14	-15.65	-14.3	40.03	36.23	33.02
MU2	4.34	10.3	13.71	15.6	21.48	28.79
N2	3.94	6.51	8.65	12.66	11.01	12
NU2	-4.81	-2.83	-1.11	12.34	12.88	13.83
M2	1.4	3.47	5.17	11.01	10.58	10.94
S2	3.92	5.88	7.42	9.04	9.44	10.6
K2	3.4	5.43	7.01	8.76	9.15	10.4
M4	29.35	31.6	32.79	49.11	52.81	58.52
MS4	25.32	27.96	40.32	44.81	50.99	56.33
M6	31.03	27.5	39.65	58.97	58.96	59.94
	Mean complex error			**RMS complex error**		
Tidal Constituent	A=0.002	Control	A=0.003	A=0.002	Control	A=0.003
Q1	0.61	0.75	0.87	0.64	0.79	0.93
O1	1.33	1.75	2.13	1.5	1.92	2.33
P1	0.79	0.76	0.77	0.89	0.86	0.87
K1	1.81	1.99	2.16	2.15	2.28	2.45
2N2	2.94	2.62	2.34	4.41	3.96	3.56
MU2	1.99	2.19	2.93	2.93	2.87	3.93
N2	4.68	5.87	7.59	5.51	6.84	8.95
NU2	1.25	1.09	1.19	1.39	1.29	1.5
M2	19.64	23.77	32.59	25	29.23	39.77
S2	8.18	8.95	11.98	10.19	10.96	14.91
K2	2.36	2.61	3.56	2.86	3.13	4.29
M4	7.77	7.72	7.82	9.78	9.65	9.88
MS4	5.62	5.59	5.71	7.59	7.52	7.79
M6	2.47	2.5	2.57	3.37	3.34	3.37

6. Tidal boundary forcing

6.1 Harmonic constituents

Boundary forcing is applied as the sum of a number of tidal constituents, specified in a namelist. Whilst the tides in the real world can be split into a few hundred constituents, many of these are caused by near-coast refraction and/or give very small perturbations to total sea level change relative to other factors. As such it is not necessary, or computationally efficient, to apply forcing from each known constituent on the model boundaries. Currently the operational 3-d baroclinic version of the AMM7 model has boundary forcing from 15 tidal constituents (Q1, O1, P1, K1, 2N2, MU2, N2, NU2, M2, L2, T2, S2, K2, M4 and S1). CS3X is forced with 26; 14 of those are in common with the AMM7 (Q1, O1, P1, K1, 2N2, MU2, N2, NU2, M2, L2, T2, S2, K2, M4) along with an additional 12 (2MK6, 2MS6, 2SM2, 3M2S2, Lam2, M6, MK3, MN4, MNS2, MO3, MS4, MSN2). Note that the S1 constituent is not used in CS3X but is used in the AMM7. To determine the benefit of these additional 12 constituents, the NEMO-surge configuration was run with just the 14 constituents in common between the two sets, whilst the control run uses the CS3X set of 26 constituents. S1 has limited effect, and so is not included in these experiments.

Whilst the additional constituents will obviously affect the total sea surface height, there will also be impacts on the 14 assessed constituents. This report focuses on those impacts so as to allow comparison with the perturbed bathymetry and perturbed bottom friction coefficient experiments.

6.2 Results

Impacts on the main tidal constituents are very limited, as can be seen in table 3, which shows summary statistics for the runs. This is due to the open boundaries of NEMO-surge being located in deep water far from the shelf. The mean complex error, for example, rarely differs by more than 0.02 other than for the MS4 and M6 tidal constituents. This is unsurprising as these constituents are not included in the limited dataset, and so are present in the boundary forcing of the control run, but absent from the perturbed run. The constituents for which boundary forcing is present in both runs show very limited effects due to the additional constituents.

Table 3: Summary results from sensitivity testing of input harmonic constituents – overall model-observation errors in amplitude (m), phase (degrees) and complex error from combined UK tide gauge locations

	Mean amplitude error		RMS amplitude error	
Tidal Constituent	Control (26 constituents)	14 constituents	Control (26 constituents)	14 constituents
Q1	-0.5	-0.49	0.65	0.65
O1	-0.61	-0.61	1.17	1.17
P1	0.09	0.09	0.49	0.49
K1	-1.16	-1.16	1.49	1.49
2N2	1.25	1.25	2.02	2.01
MU2	-0.09	-0.09	1.51	1.51
N2	-1.94	-1.96	3.32	3.32
NU2	0.46	0.48	0.8	0.82
M2	-7.98	-7.97	14.26	14.26
S2	-1.77	-1.77	4.62	4.62
K2	-0.68	-0.68	1.64	1.64
M4	0.09	0.1	6.77	6.79
MS4	0.38	0.24	5.13	5.17
M6	0.23	0.28	2.17	2.26
	Mean phase error		**RMS phase error**	
Tidal Constituent	Control (26 constituents)	14 constituents	Control (26 constituents)	14 constituents
Q1	8.26	8.25	18.73	18.72
O1	10.29	10.3	13.52	13.52
P1	-0.21	-0.23	14.98	14.99
K1	-1.05	-1.04	12.51	12.51
2N2	-15.65	-15.64	36.23	36.22
MU2	10.3	10.27	21.48	21.46
N2	6.51	6.49	11.01	11
NU2	-2.83	-2.71	12.88	12.97
M2	3.47	3.47	10.58	10.58
S2	5.88	5.87	9.44	9.42
K2	5.43	5.42	9.15	9.16
M4	31.6	31.62	52.81	52.61
MS4	27.96	28.06	50.99	54.77
M6	27.5	28.55	58.96	56.79
	Mean complex error		**RMS complex error**	
Tidal Constituent	Control (26 constituents)	14 constituents	Control (26 constituents)	14 constituents
Q1	0.75	0.75	0.79	0.79
O1	1.75	1.76	1.92	1.93
P1	0.76	0.77	0.86	0.86
K1	1.99	1.99	2.28	2.28
2N2	2.62	2.62	3.96	3.96
MU2	2.19	2.18	2.87	2.87
N2	5.87	5.86	6.84	6.83
NU2	1.09	1.1	1.29	1.31
M2	23.77	23.79	29.23	29.24
S2	8.95	8.95	10.96	10.95
K2	2.61	2.61	3.13	3.13
M4	7.72	7.72	9.65	9.66
MS4	5.59	5.71	7.52	7.62
M6	2.5	2.58	3.34	3.47

It is perhaps unsurprising that individual constituents show extremely limited effects due to boundary forcing of additional constituents, so the effect on the full tidal signal was also investigated. However, as the 14 constituents present in both experiments account for the majority of the tidal signal, impacts on this were again shown to be very small. The total tidal signal from the model was plotted for the first two weeks of January for each tide gauge location. Leith showed the greatest impact due to the additional constituents, as illustrated in figure 12. However the majority of the ports showed no noticeable difference. The additional tidal constituents have extremely limited impact on the total tidal sea surface height signal.

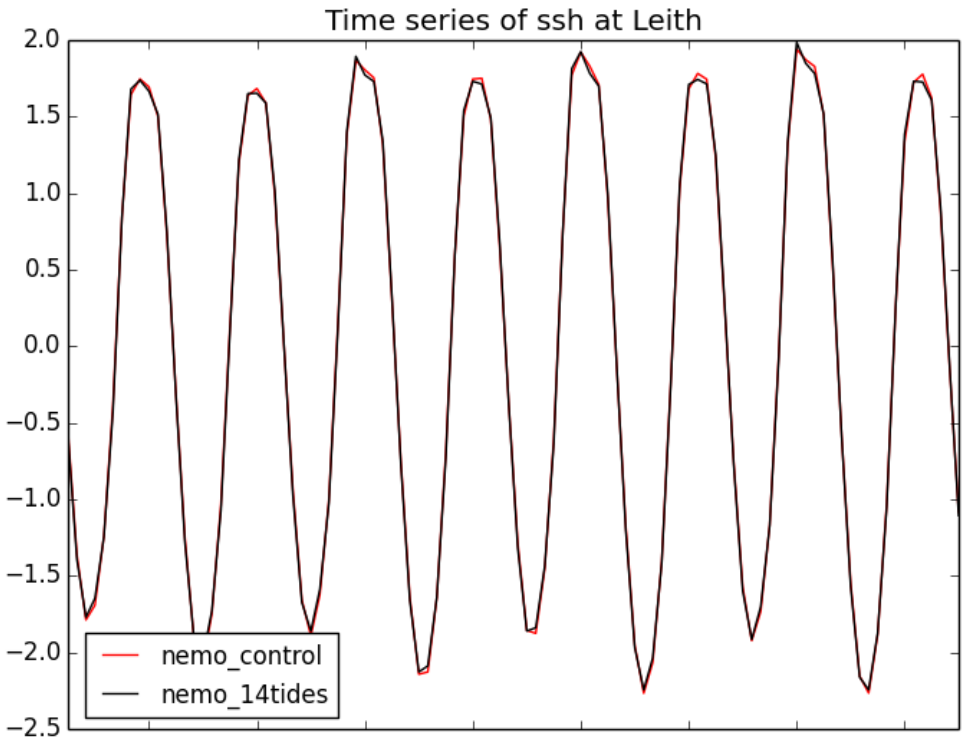

Figure 12: Full sea surface height signal from tide only run, at Leith for first fortnight in January 2004

7. NEMO-surge versus CS3X comparison

Following these sensitivity tests and further tuning experiments, a tidal version of NEMO-surge has been defined and assessed. This configuration uses the EMODnet bathymetry, with a few manual edits as discussed in section 4, a minimum depth of 6m in most locations, and 10m minimum depth in the Bristol Channel and the Gulf of St Malo. The boundaries are forced with data from 26 tidal constituents. Following tuning experiments, a value of 0.0024 for the bottom friction coefficient was adopted.

This fixed tidal version of NEMO has been assessed. The model predicted tide at each gauge location has been compared to CS3X. Figures 13 to 16 show the errors for both CS3X and NEMO-surge for the M2 constituent at each port. The two models give comparable but different results, with a number of ports showing errors of opposite signs for the two models. Within this there are some locations where CS3X better matches the observations whilst there are also locations where NEMO-surge gives the lowest errors.

Along the east coast of Scotland and England NEMO-surge has lower complex error for the majority of ports, and improved phase errors for 7 of the 12 ports. Amplitude errors only show improvements for 4 ports, with NEMO-surge generally under-predicting amplitudes. However the under-prediction biases are relatively small, being 5-10% of the overall amplitudes for all but two ports (Leith and Cromer).

Amplitude errors along the south coast of England are reasonably consistent for both models. Phase at Bournemouth is significantly improved in NEMO-surge. The majority of other ports show increased phase errors, but these are small (within 5 degrees at all sites except Plymouth and Portsmouth), whilst the CS3X performance is excellent along the south coast. Complex errors are increased for the majority of ports, primarily due to the increase in phase errors.

For the west coasts of England and Wales phase in NEMO-surge is at least a good as, if not better than CS3X. Complex error is improved for 10 of the 14 ports, with phase errors improved for 9 ports. Amplitudes are generally underestimated in NEMO-surge around the Bristol Channel, but these are still comparable to CS3X (with half of the ports showing reduced errors) and are less than 10% of the overall amplitudes at these locations.

The west coast Scottish ports are improved in NEMO-surge; amplitude errors are reduced in just over half the ports, phase is improved in almost all, and complex error reduced in 5 of the 7 ports. The large phase error, in both models, at Port Ellen is related to the proximity of this location to an amphidromic point where the tidal elevation signal is weak (observed M2 amplitude approximately 16cm).

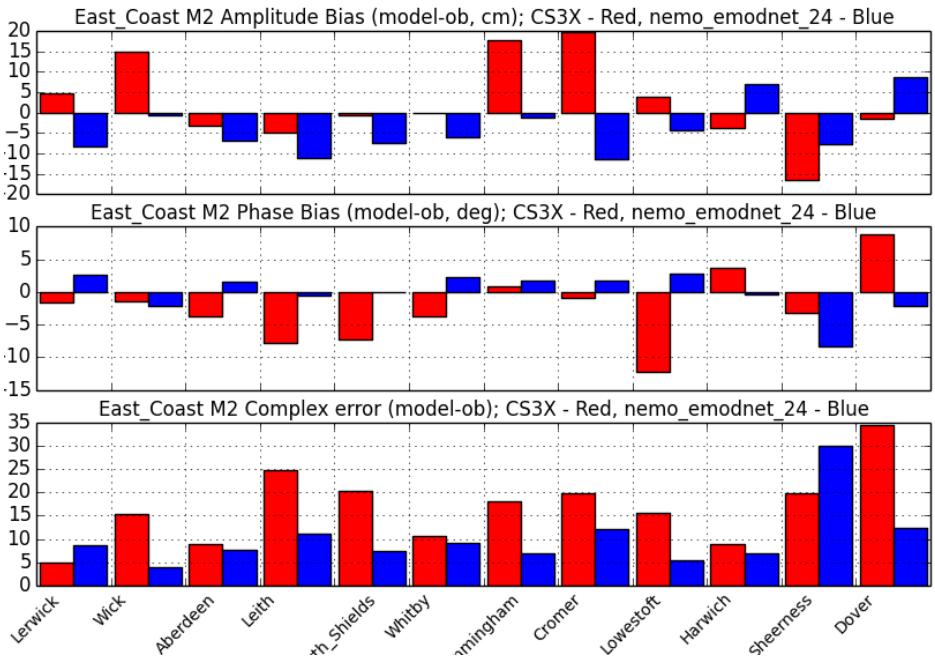

Figure 13: Errors in amplitude (m), phase (degrees) and complex error of the M2 constituent for CS3X and NEMO_EMODnet at each port on the East Coast of England

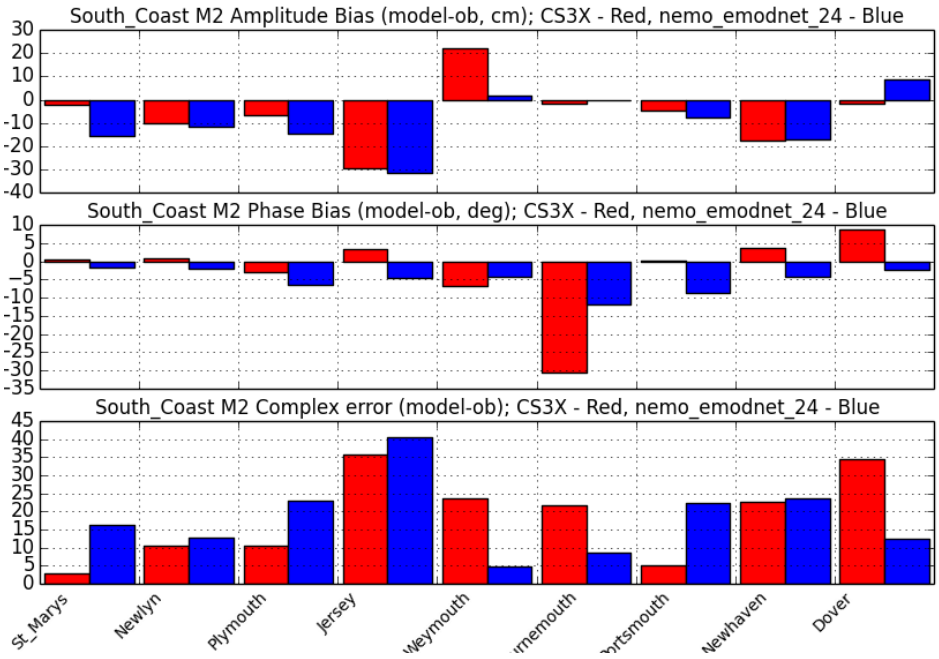

Figure 14: Errors in amplitude (m), phase (degrees) and complex error of the M2 constituent for CS3X and NEMO_EMODnet at each port on the South Coast of England

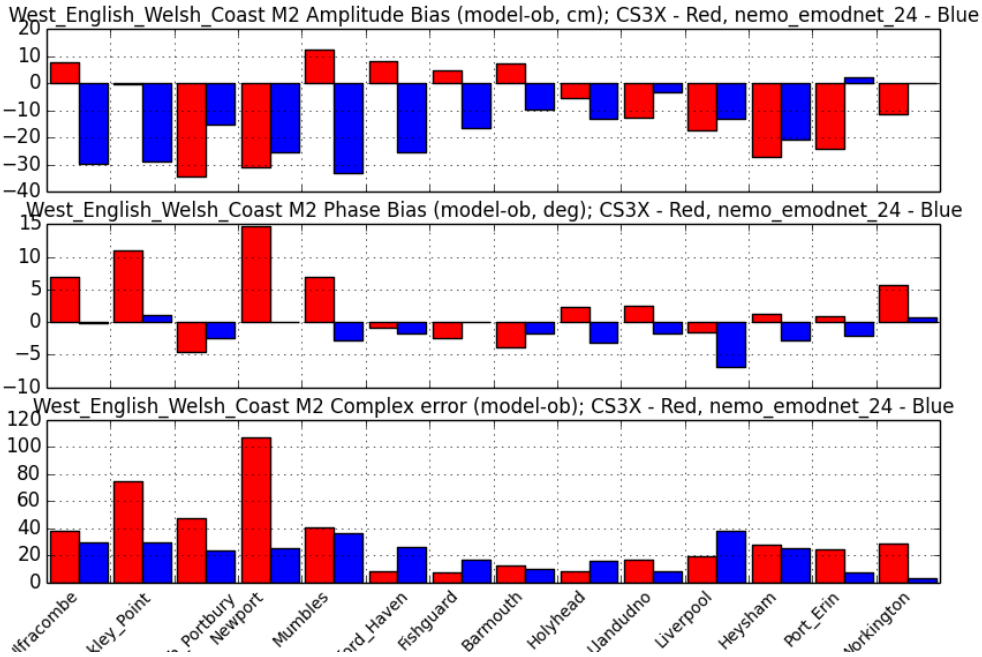

Figure 15: Errors in amplitude (m), phase (degrees) and complex error of the M2 constituent for CS3X and NEMO_EMODnet at each port on the West English and Welsh Coasts

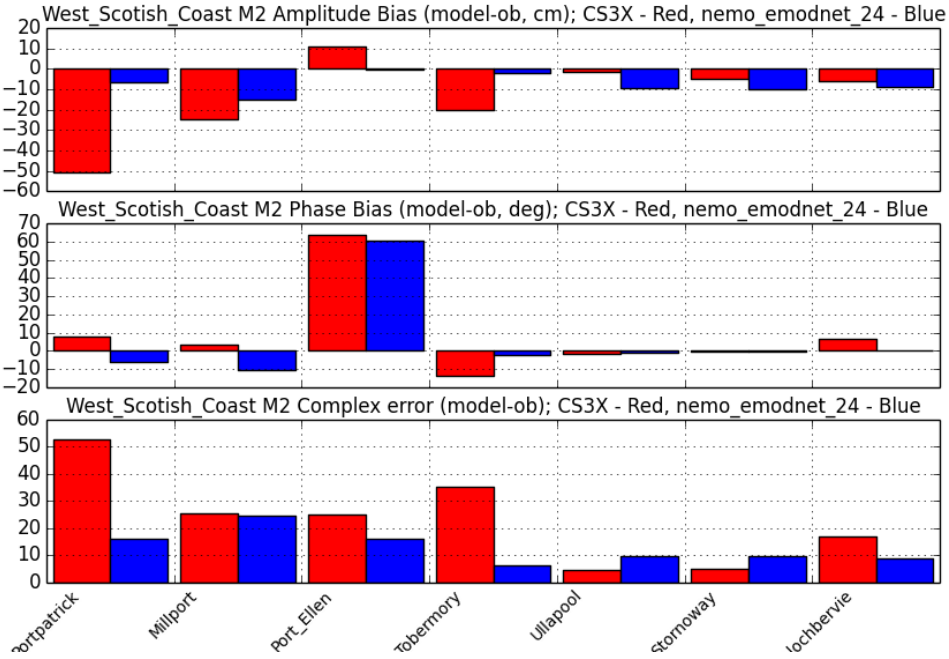

Figure 16: Errors in amplitude (m), phase (degrees) and complex error of the M2 constituent for CS3X and NEMO_EMODnet at each port on the Scottish Coast

Table 4 summarises the results for each constituent, averaged over all tide gauges. This shows reduced errors in many constituents with the NEMO-surge configuration. For example, for 10 of the 14 constituents the mean complex error is lower in NEMO-surge compared to the existing CS3X model.

Table 4: Summary results from CS3X and NEMO-surge – overall errors in model-observed amplitude (m), phase (degrees) and complex error from combined UK tide gauge locations

	Mean amplitude error		RMS amplitude error	
Tidal Constituent	CS3X	NEMO-surge	CS3X	NEMO-surge
Q1	-0.2	-0.51	0.5	0.68
O1	-1.37	-0.31	1.64	0.66
P1	-0.17	0.52	0.46	0.78
K1	-0.51	-0.41	1.01	1.07
2N2	1.56	1.14	2.27	2.03
MU2	-0.53	-0.06	3.72	1.61
N2	-1.61	-1.58	4.12	3.09
NU2	0.02	0.18	0.77	0.58
M2	-5.9	-10.5	16.66	14.49
S2	-2	-1.2	6.46	3.31
K2	-1.12	-0.43	2.45	1.35
M4	-0.96	1.52	5.82	6.64
MS4	-0.68	1.3	4.46	4.4
M6	0.99	0.18	2.51	1.72
	Mean Phase error		**RMS phase error**	
Tidal Constituent	CS3X	NEMO-surge	CS3X	NEMO-surge
Q1	-6.77	1.06	18.88	18.59
O1	5.77	1.77	16.98	7.87
P1	-9.57	-6.64	11.63	11.65
K1	-5.02	-7.36	9.94	10.35
2N2	-11.27	-13.01	33.98	40.44
MU2	4.68	-9.87	40.43	32.66
N2	3.89	2.64	15.29	14.82
NU2	1.43	-4.37	27.24	28.67
M2	1.08	-0.71	12.45	10.31
S2	1.83	-1.4	9.38	7.69
K2	2.25	-2.05	10.45	9.08
M4	22.85	3.08	66.6	30.4
MS4	2.82	2.68	56.62	35.33
M6	20.7	-4.88	74.94	71.55
	Mean complex error		**RMS complex error**	
Tidal Constituent	CS3X	NEMO-surge	CS3X	NEMO-surge
Q1	0.67	0.77	0.89	0.85
O1	1.87	0.7	1.98	0.81
P1	0.75	0.92	0.83	0.98
K1	1.7	1.56	1.94	1.95
2N2	2.86	2.92	3.82	4.14
MU2	3.95	2.01	5.97	2.53
N2	5.51	3.47	6.81	4.02
NU2	1.21	1.23	1.7	1.34
M2	23.48	16.16	30.61	18.99
S2	9.24	5.07	12.06	5.86
K2	3.07	1.92	3.84	2.17
M4	7.25	5.6	8.88	7.95
MS4	4.91	3.77	6.38	5.75
M6	3.02	1.87	4.04	2.31

8. Discussion and conclusions

A 2-d depth-averaged tidal NEMO-surge configuration, with horizontal resolution of 7km using EMODnet bathymetry, has been developed by the NOC and the Met Office. The new configuration gives good results in terms of harmonic tidal constituents derived at UK Class A tide gauges when compared to observations. The results are comparable to, if not better than, tide only runs of the operational surge model CS3X.

It is clear from the experiments presented in this study that the model tide performance is sensitive to bathymetry. This sensitivity is not localised to the area amended, but follows the tidal propagation through the domain. Bathymetric amendments were also shown to have greater impact on the tidal phase than the tidal amplitudes.

The model is also sensitive to the coefficient used in the bottom friction formulation. The tidal amplitudes were shown to have greater sensitivity to bottom friction than to bathymetric changes; however sensitivity of the tidal phase was comparable in both cases.

Sensitivity testing for tidal forcing showed that boundary forcing of additional constituents, over and above the 14 constituents common to CS3X and a baroclinic NEMO model for the UK shelf seas, has a very limited effect on other constituents due to the placement of the open boundary. Since the tidal signal is dominated by a few primary constituents (e.g. M2, S2), these additional constituents also have very limited impacts on the total tidal signal.

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